Recirculating Linear Accelerators for Future Muon Facilities

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Motivation – Scientific Case

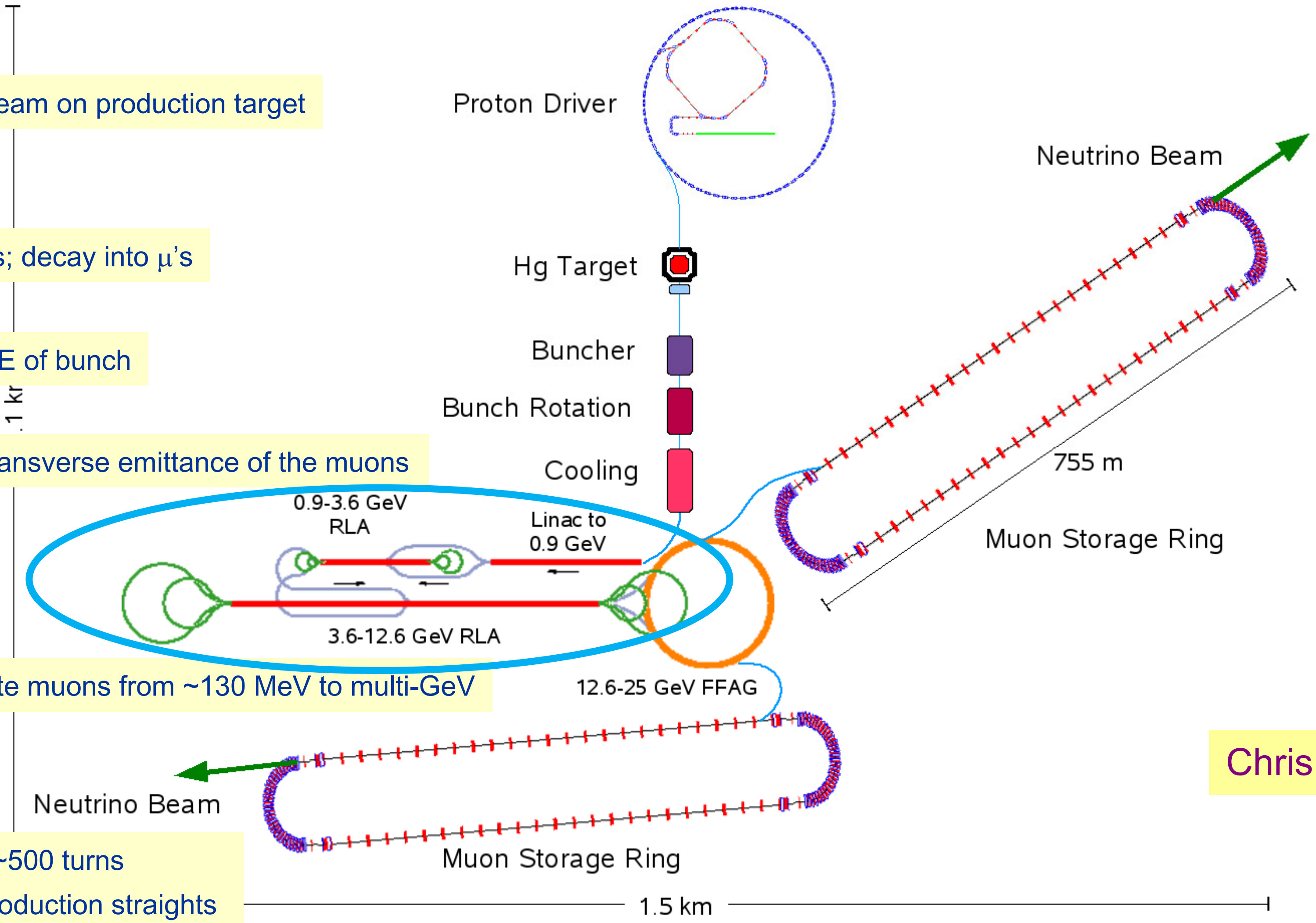
- **Muon Colliders** and **Neutrino Factories** are attractive options for future facilities aimed at achieving the highest lepton-antilepton collision energies (e.g. to mass-produce Higgs bosons in s-channel) and precision measurements of parameters of the neutrino mixing matrix with intense (10^{14} μ/sec), small divergence neutrino beams with well-understood systematics.
- Their performance and feasibility depend strongly on how well a muon beam can be produced, cooled and accelerated to multi-GeV and TeV energies.
- Recent progress in muon cooling and acceleration (International Design Study and prototype tests) encourages the hope that such facilities can be built during the next decade…

Opportunities and Challenges

- Future **Muon Facilities** will require innovative beam techniques to:
  - collect and cool muons
  - longitudinally compress and ‘shape’ them into a beam
  - rapidly accelerate them to multi-GeV (NF) and TeV (MC) energies
- New challenges and opportunities follow from the nature of the muon:
  - it has a short lifetime (2.2 μsec) in its own rest frame
  - it is produced in a tertiary process into a large emittance ($p + A \rightarrow \pi \rightarrow \mu$)
  - it does not undergo nuclear interaction with matter; it only ’sees’ Coulomb forces
  - it is a ‘heavy-lepton (m_μ = 105 MeV/c^2); it does not generate significant synchrotron radiation even at extremely high energy and in strong magnetic fields – **Recirculating Linear Accelerators** (RLA) are possible

Neutrino Factory – International Design Study

- primary beam on production target
- create π's; decay into μ's
- reduce ΔE of bunch
- reduce transverse emittance of the muons
- accelerate muons from ~130 MeV to multi-GeV
- store for ~500 turns
- Long ν production straights



Chris Prior

Muon Acceleration – Choice of Technology

- To ensure adequate survival rates of short-lived muons the accelerator must provide high average gradient, while maintaining very large transverse and longitudinal accelerator acceptances.
  - The above requirement drives the design to low RF frequency, e.g. 200 MHz.
  - If normal-conducting cavities at that frequency were used, the required high gradients would demand uneconomically high peak RF sources.
  - Superconducting RF is a much more attractive solution – the RF power can then be delivered to the cavities over an extended time, and thus RF source peak power can be reduced.
- While recirculation (RLA) provides significant cost savings over a single linac, it cannot be used at low energy since the beam is not sufficiently relativistic and will therefore cause a phase slip for beams in higher passes

Linac-RLA Acceptance

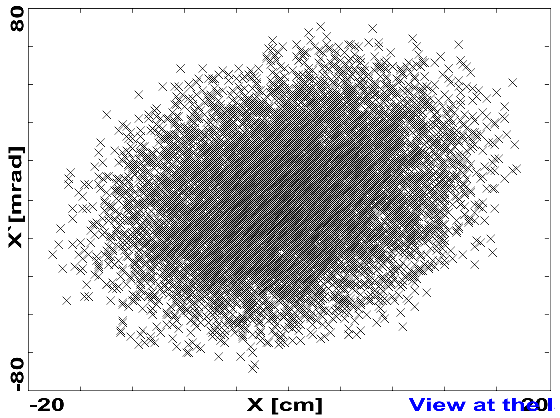
Initial phase-space after the cooling channel at 220 MeV/c

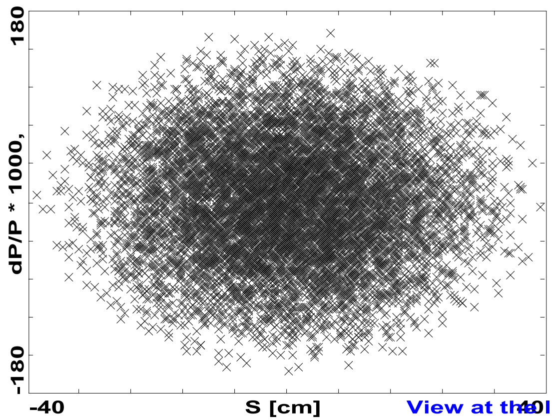
International Design Study		ε_{rms}	$A = (2.5)^2\ \varepsilon$
normalized emittance: $\varepsilon_x/\varepsilon_y$	mm·rad	**4.8**	**30**
longitudinal emittance: ε_l	mm	**24**	**150**
$(\varepsilon_l = \sigma_{\Delta p}\ \sigma_z/m_\mu c)$			
momentum spread: $\sigma_{\Delta p/p}$		**0.07**	**±0.17**
bunch length: σ_z	mm	**165**	**±412**

$\beta_{x,y}$ = 2.74 m

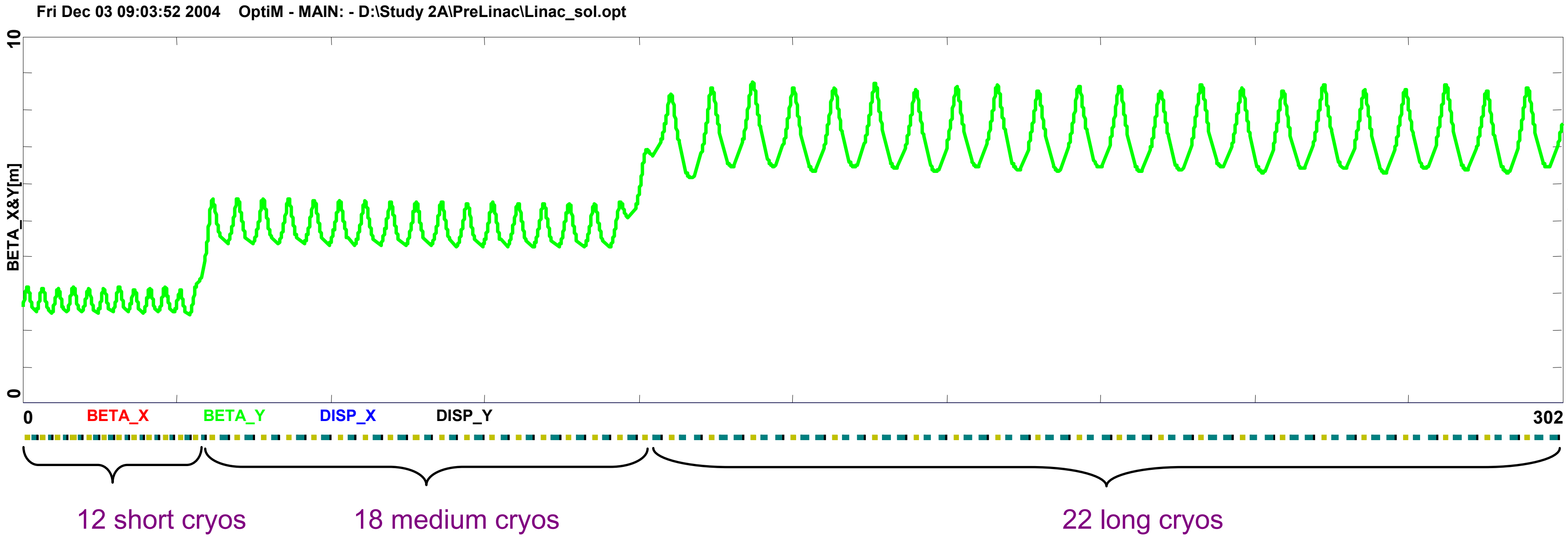
$\alpha_{x,y}$ = -0.356

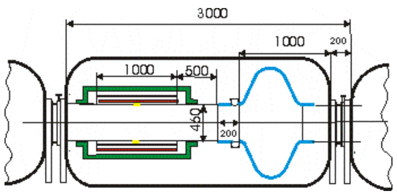
$\beta\gamma$ = 2.08



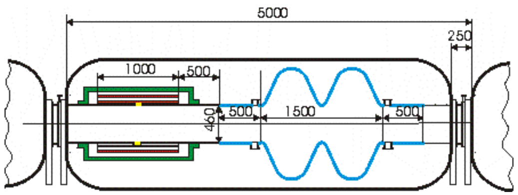


Linear Pre-accelerator – 3 GeV

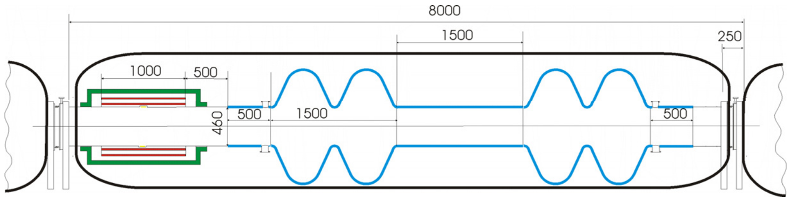




1.5 Tesla solenoid



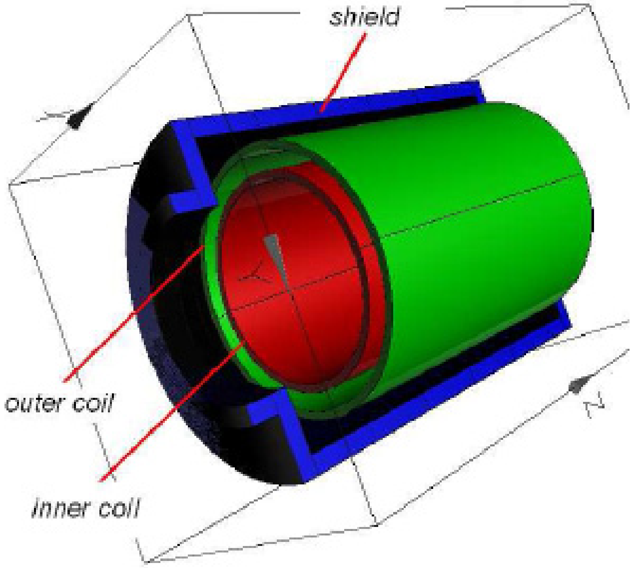
2 Tesla solenoid



4 Tesla solenoid

To achieve fast field drop from solenoid to cavity the solenoid has an **outer counter-coil**, which intercepts its magnetic flux, and the cavity has a **SC shielding** at its outer surface. That allows one to achieve magnetic field less than **0.1 G** inside the cavity

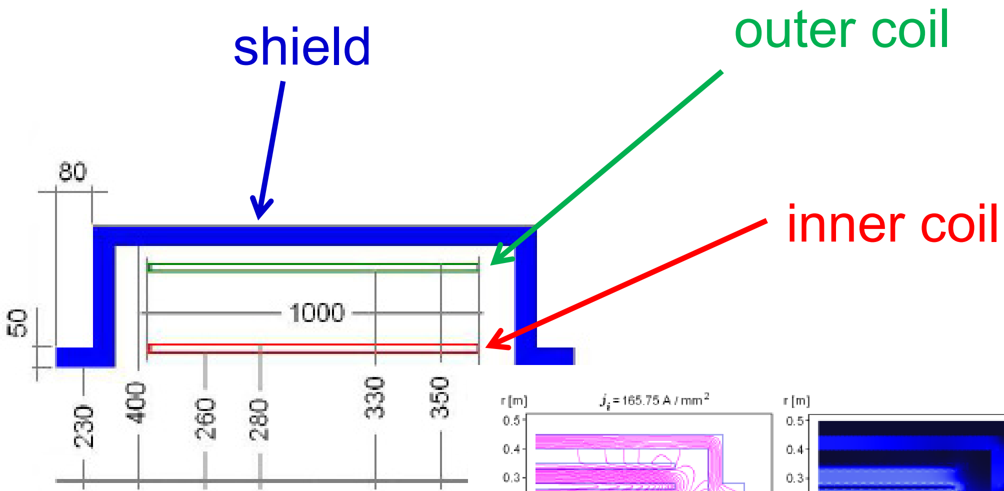
‘Soft -edge’ Solenoid Model (Superfish)



‘Soft-edge’ Solenoid

$$B_z(s)=\frac{1}{2}B_0\left[1-\tanh\left(\frac{s-L/2}{a}\right)\right]$$

$$\Phi_{edge}=\frac{1}{2}\left(\frac{e}{pc}\right)^2\left(\int_{-\infty}^{\infty}B_z^2(s)\,ds-B_0^2L\right)=-\frac{k^2a}{8}\qquad k=\frac{e}{pc}B_0$$



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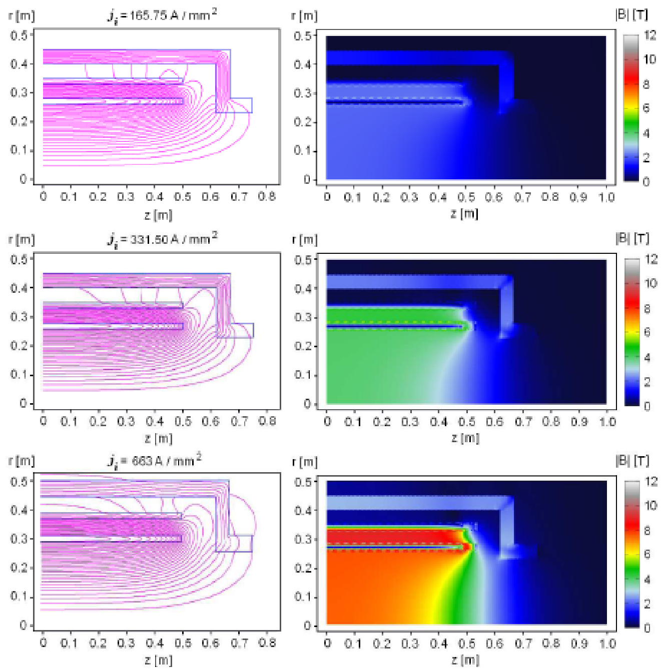
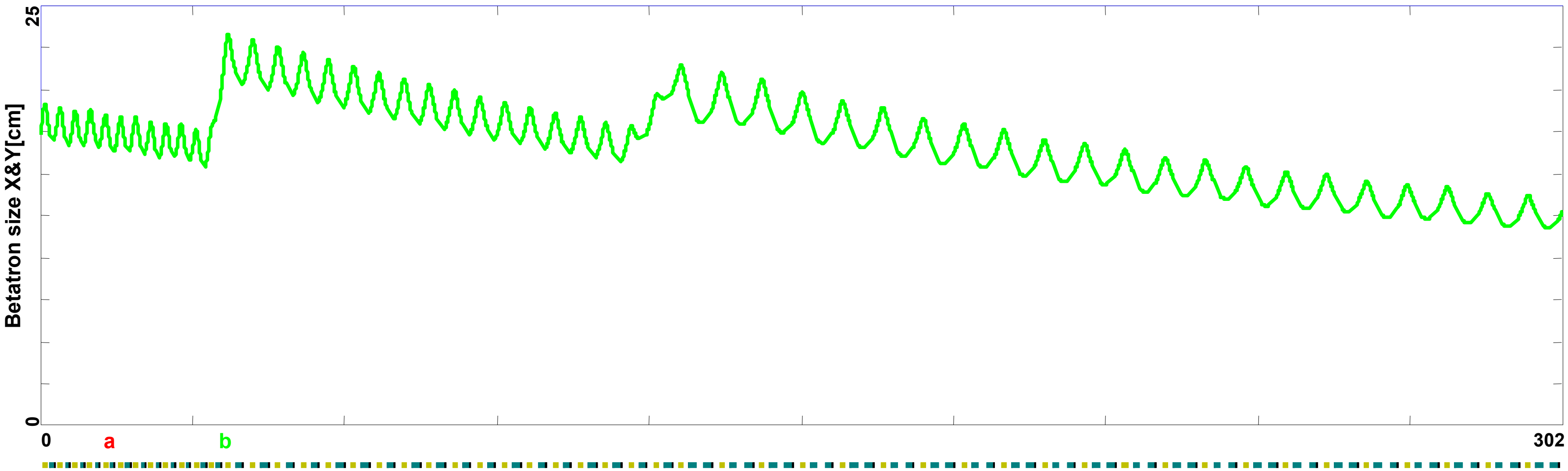
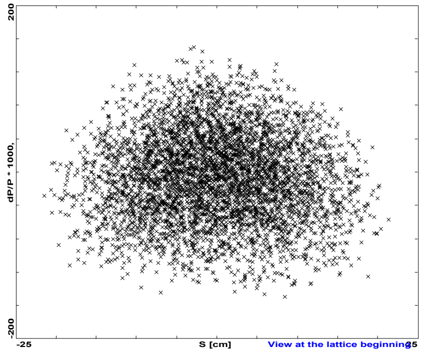
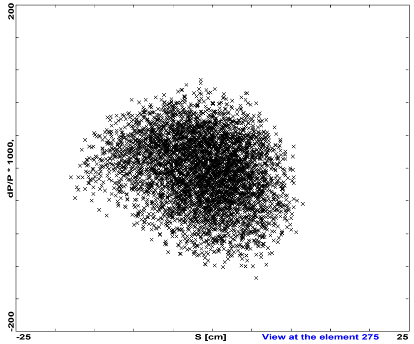
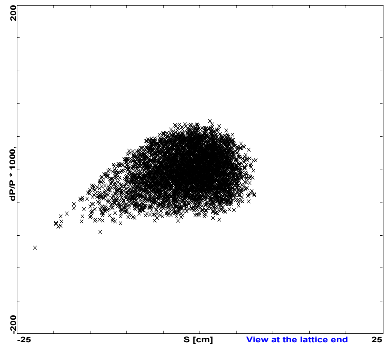


Linear Pre-accelerator – Longitudinal dynamics



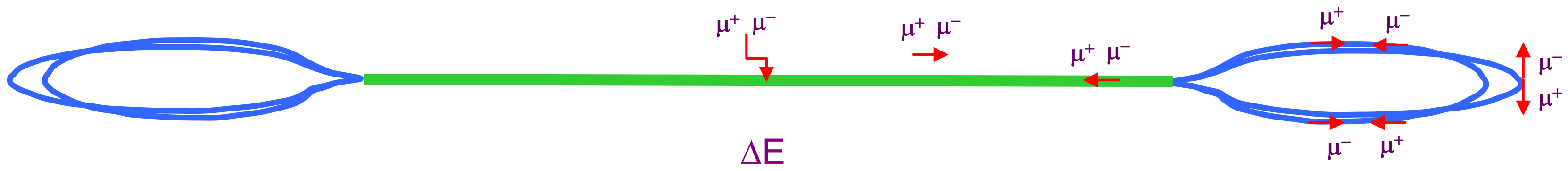






Longitudinal phase-space (s, Δp/p)   axis range: s = ±25 cm, Δp/p = ±0.2

'Racetrack' vs 'Dogbone' RLA (both μ^+ and μ^-)

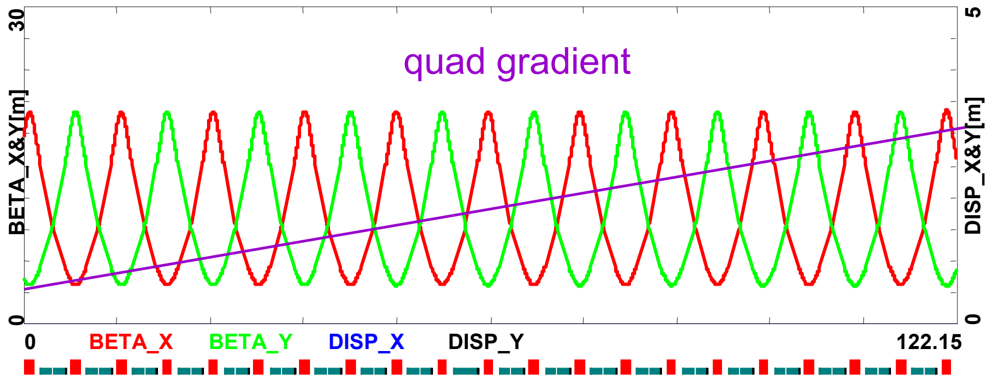


- allows both charges to traverse the Linac in the same direction (more uniform focusing profile)
- better orbit separation at linac's end ~ energy difference between consecutive passes (2ΔE)
- the droplets can be reduced in size according to the required energy
- both charge signs can be made to follow a Figure-8 path (suppression of depolarization effects)

Multi-pass 'bisected' linac Optics

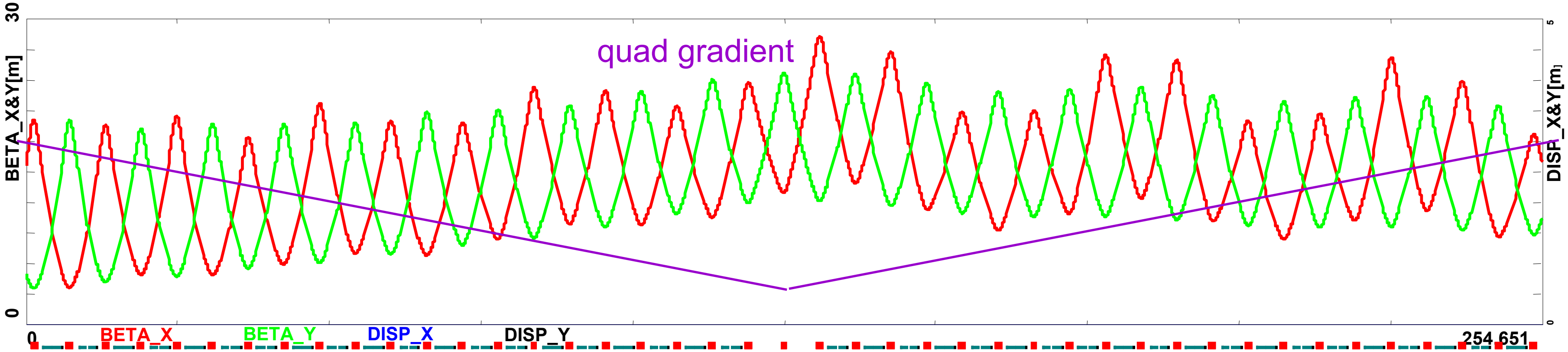
'half pass' , 3-5 GeV

initial phase adv/cell 90 deg. scaling quads with energy



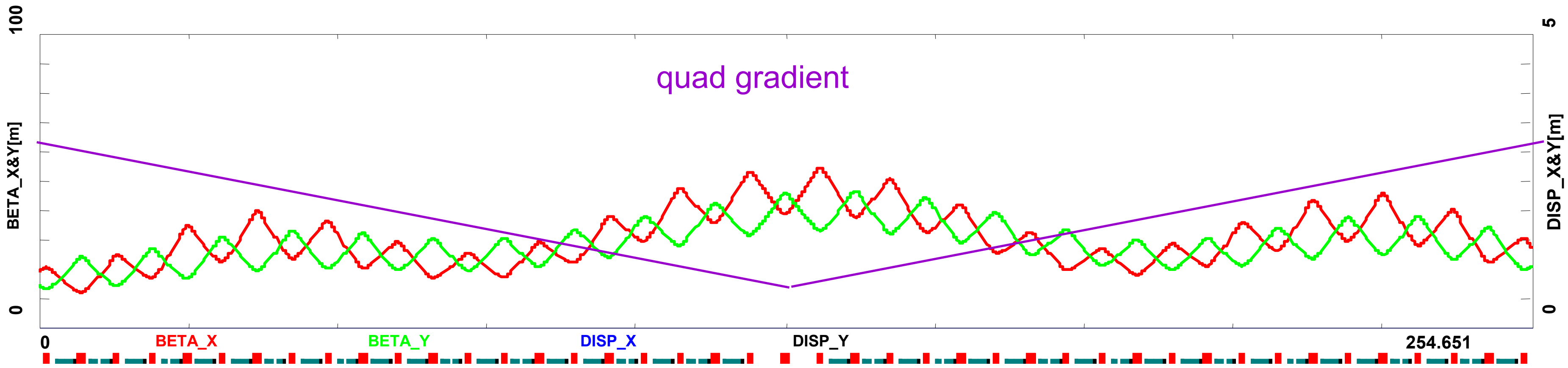
1-pass, 5-9 GeV

mirror symmetric quads in the linac

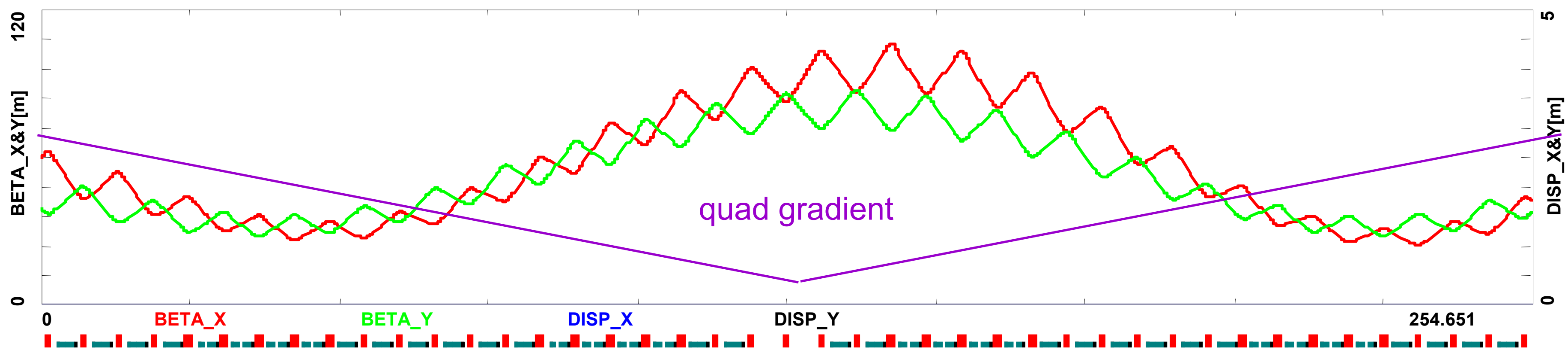


Multi-pass linac Optics

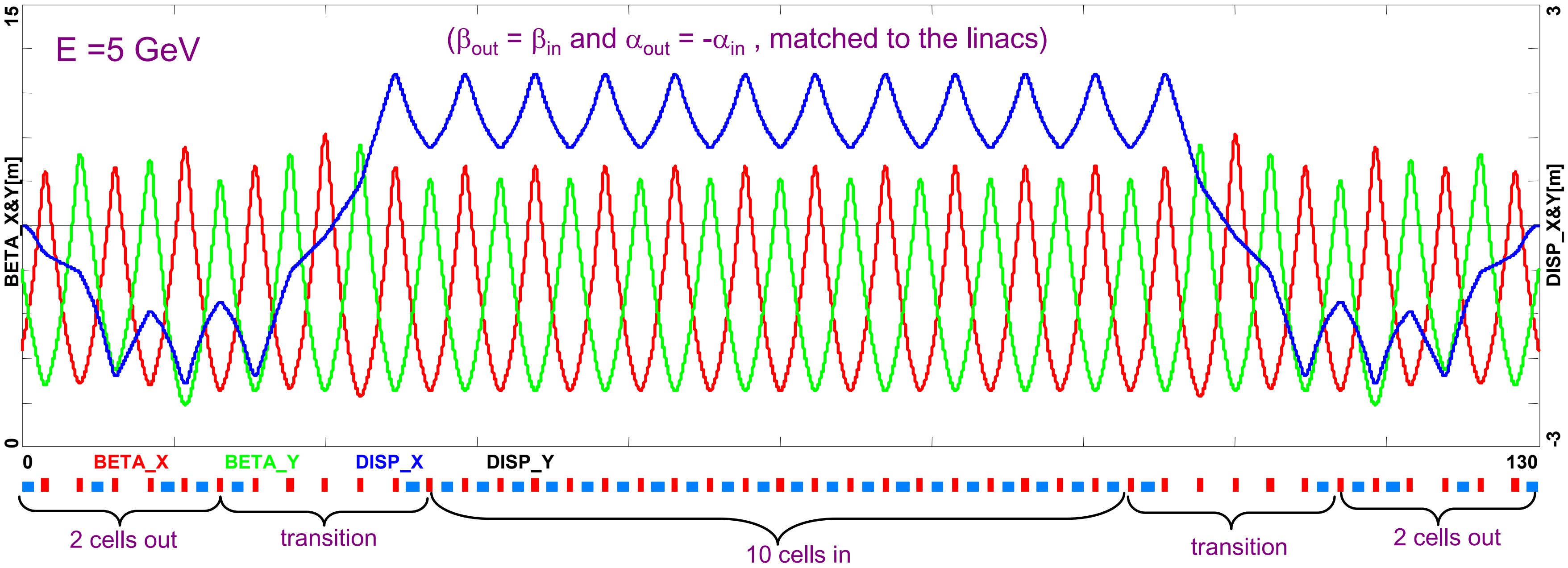
4-pass, 17-21 GeV

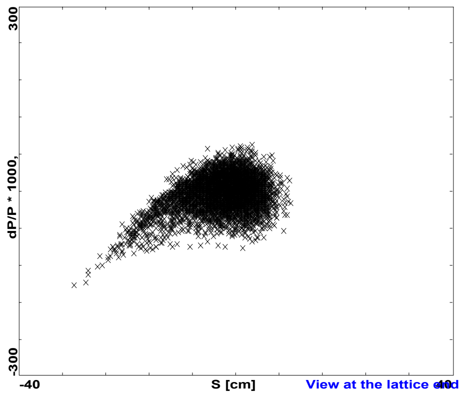


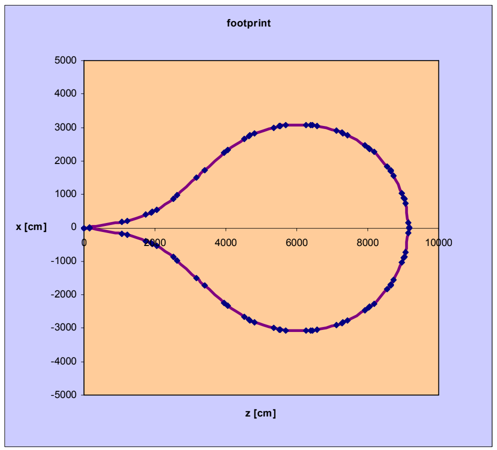
7-pass, 29-33 GeV

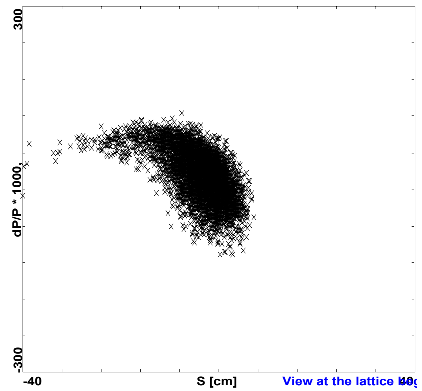


Mirror-symmetric 'Droplet' Arc – Optics

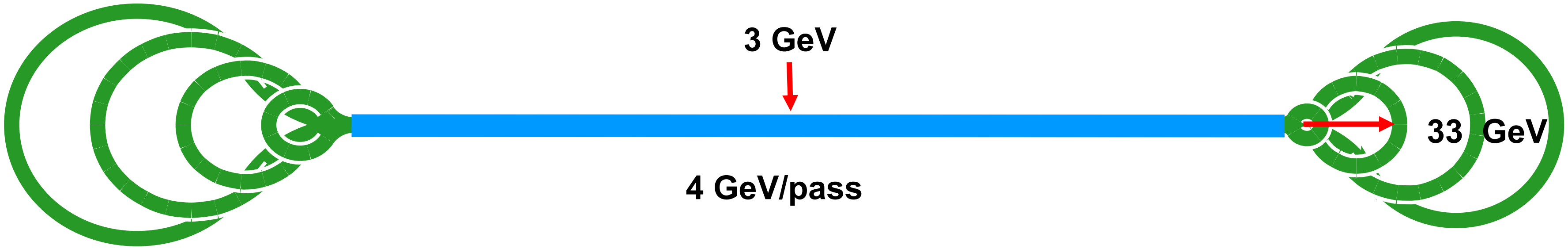








'Pulsed' vs 'Fixed' quad Dogbone RLA

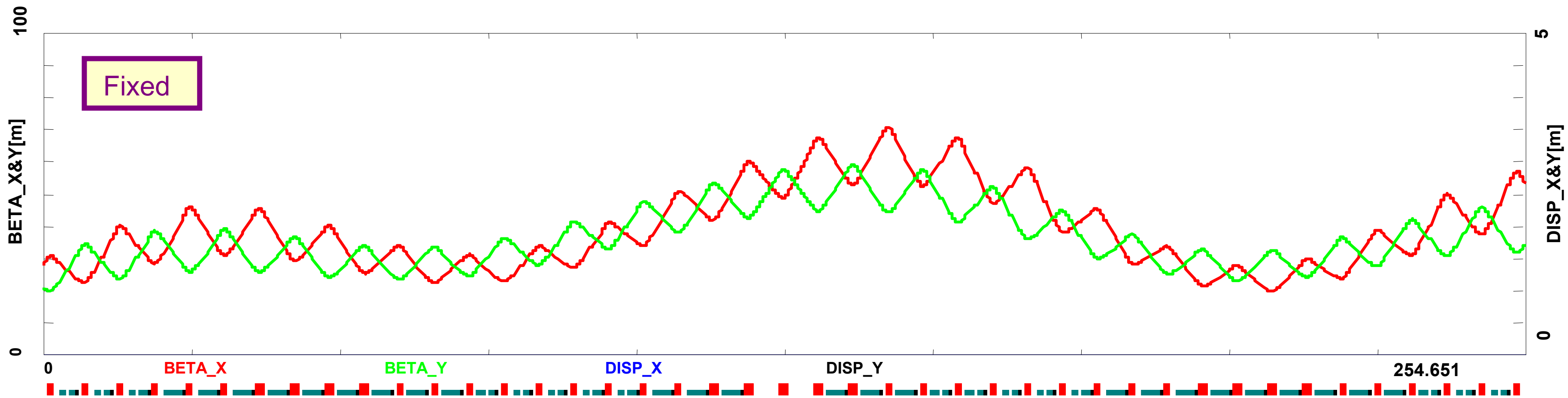


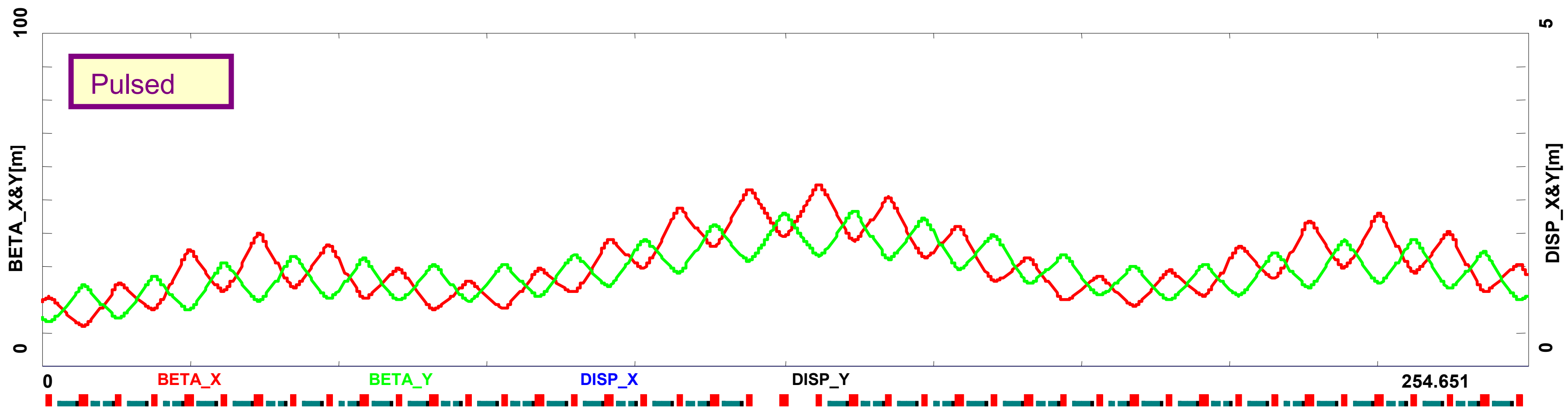
- Quad pulse would assume 500 Hz cycle ramp with the top pole field of 1 Tesla.
- Equivalent to: maximum quad gradient of G_{max} =2 kGauss/cm (5 cm bore radius) ramped over τ = 10^{-3} sec from the initial gradient of G_0 =0.1 kGauss/cm (required by 90^0 phase advance/cell FODO structure at 3 GeV) G_8 =13 G_0 = 1.3 kGauss/cm
- These parameters are based on similar applications for ramping corrector magnets such as the new ones for the Fermilab Booster Synchrotron that have 1 kHz capability

$$T \approx 8 \times \frac{500+250}{3\times 10^{-8}} \text{sec} = 2\times 10^{-5} \text{ sec}$$

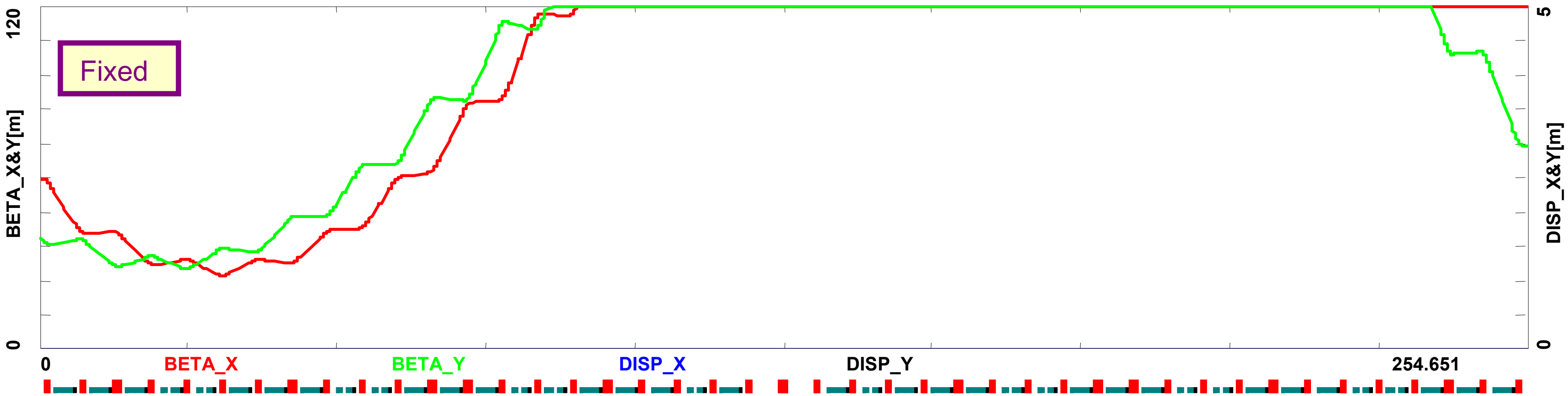
$$\frac{T}{\tau} \approx 2\times 10^{-2}$$

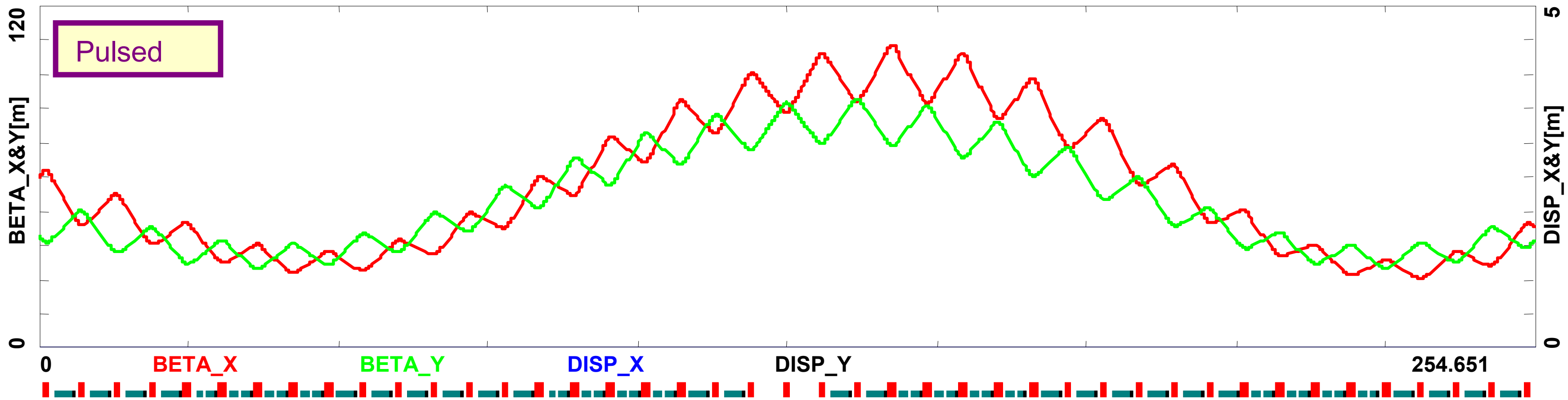
'Fixed' vs 'Pulsed' linac Optics (8-pass)





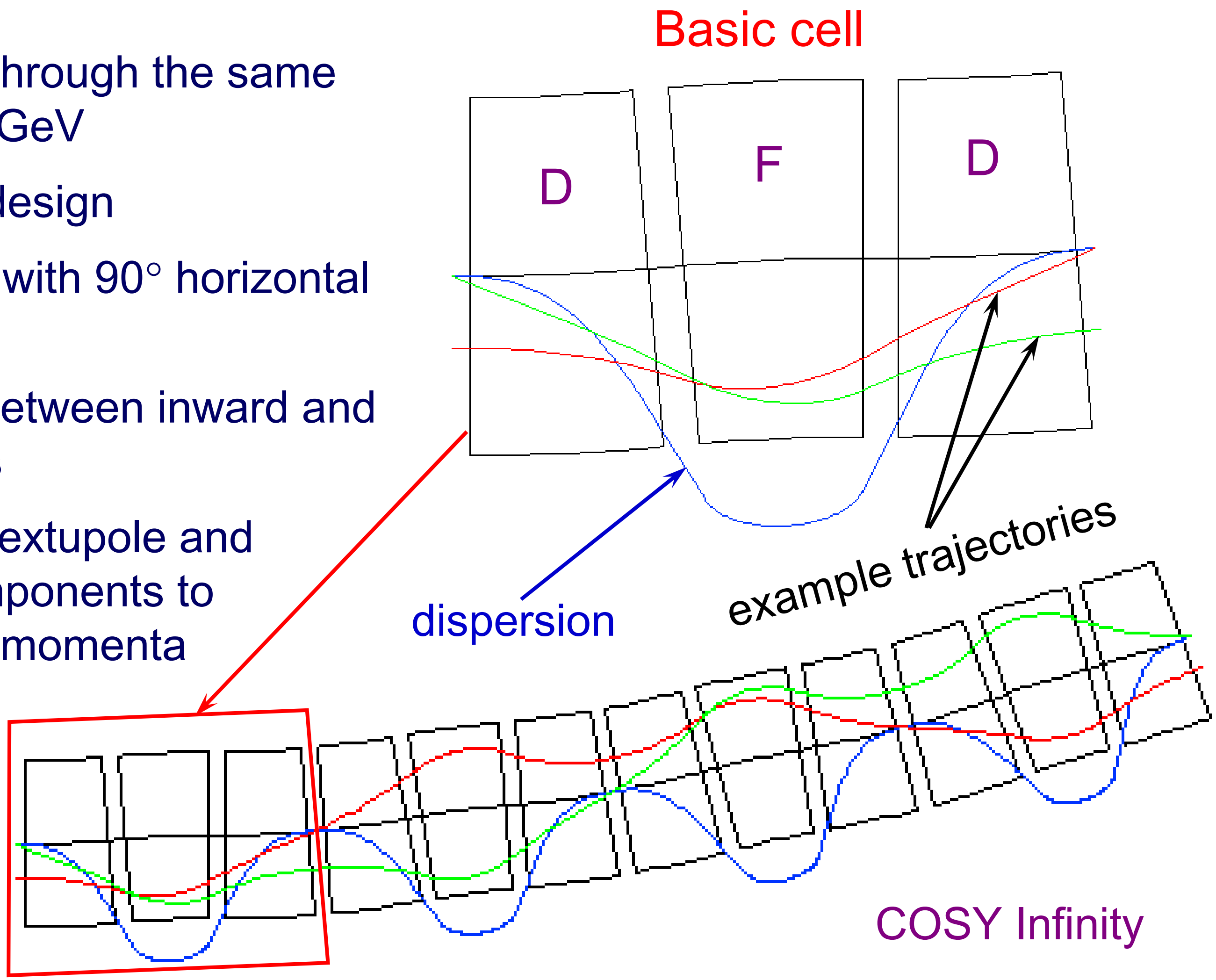
‘Fixed’ vs ‘Pulsed’ linac Optics (12-pass)



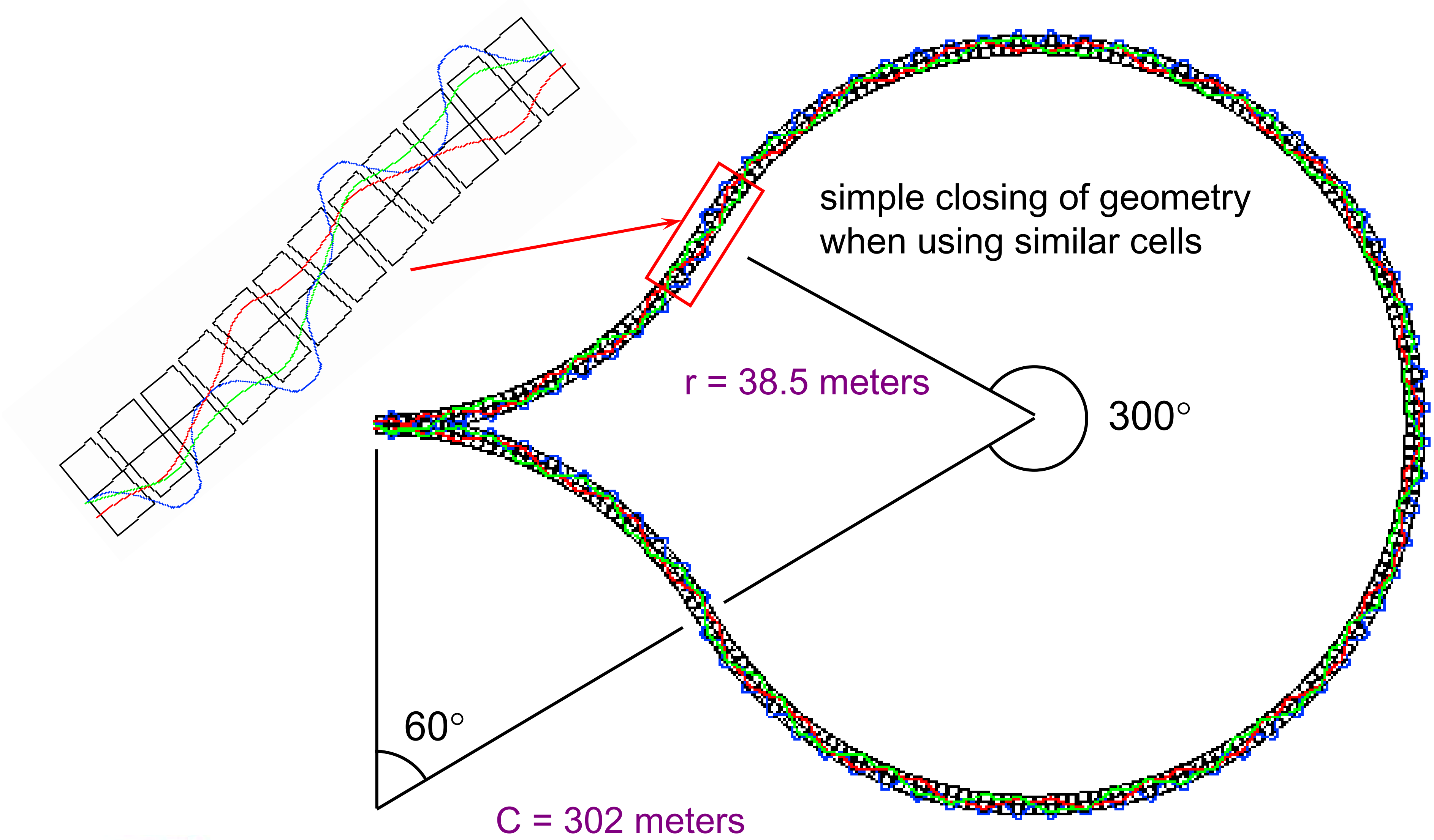


Multi-pass NS-FFAG Arc

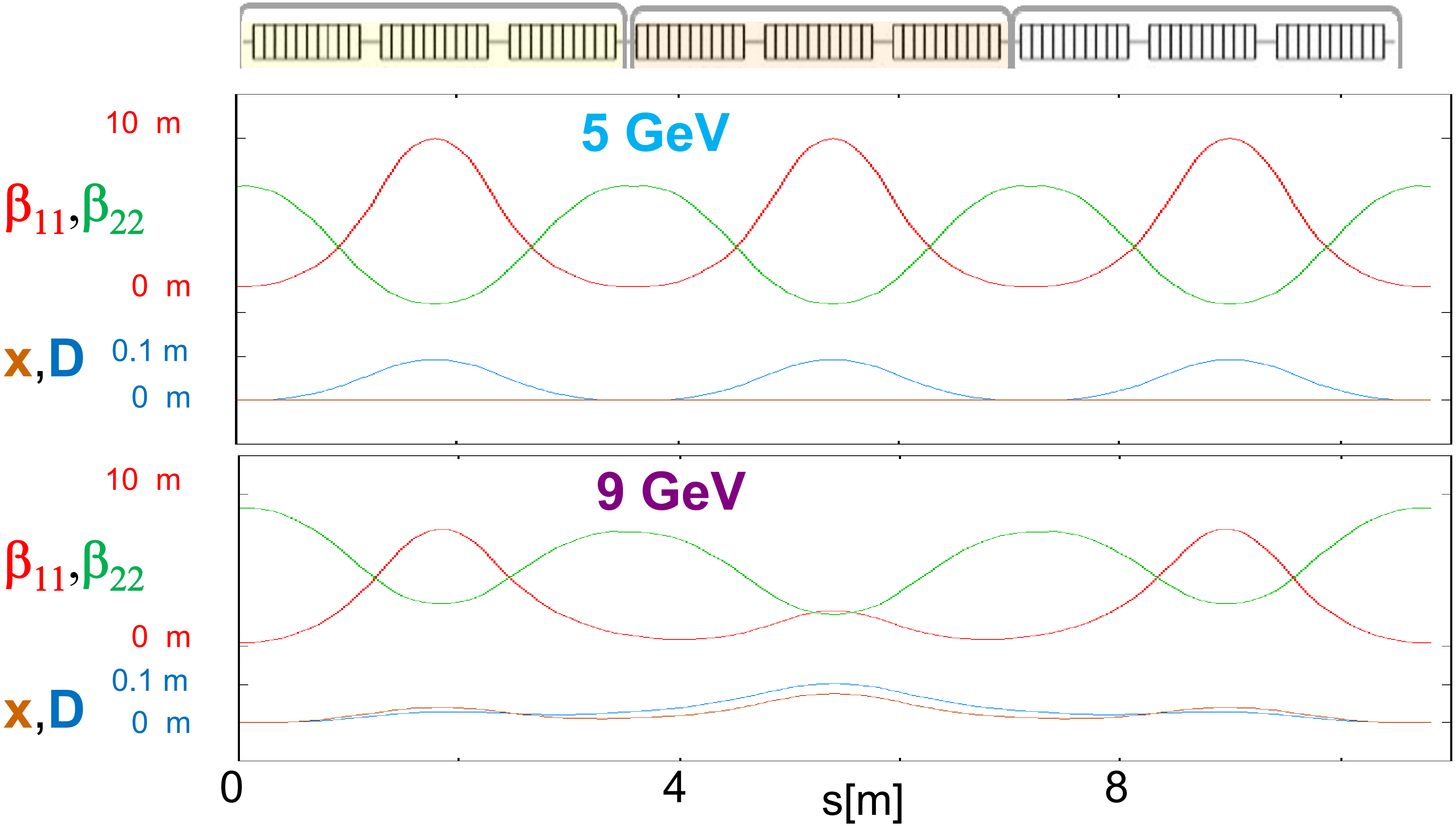
- Two or more passes through the same arc e.g. 5 GeV and 9 GeV
- NS-FFAG arc lattice design
- Achromatic basic cell with 90° horizontal phase advance
- Automatic matching between inward and outward bending cells
- Need to incorporate sextupole and higher-order field components to accommodate higher momenta



Multi-pass FFAG Arc



NS-FFAG 'Super-cell'



WEPE084: 'Muon Acceleration with RLA and Non-scaling FFAG Arcs', Morozov, Bogacz, Trbojevic

Conclusions

- **Large acceptance** muon RLAs provides rapid acceleration and effective longitudinal bunch compression via induced synchrotron motion.
- **'Dogbone'** (Single Linac) RLA has advantages over the 'Racetrack'
  - better orbit separation for higher passes
  - offers symmetric solution for simultaneous acceleration of μ^+ and μ^-
- **'Bisected'** linac Optics – mirror symmetric quad gradient along the linac
- **Pulsed linac** Optics…. even larger number of passes is possible if the quadrupole focusing can be increased as the beam energy increases
- **Multi-pass droplet Arcs** - to accommodate two consecutive passes (two neighboring energies) – **NS-FFAG** Optics based on the opposing bend combined function magnets
  - **Muon RLAs** look very encouraging and open possibility for a TeV scale acceleration.